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LABORATORY FACILITY FOR MEASUREMENT OF HOT GASEOUS PLUME RADIATIVE TRANSFER

JUNE 1981

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By

Wendell R. Watkins
Kenneth O. White

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US Army Electronics Research and Development Command
Atmospheric Sciences Laboratory
White Sands Missile Range, NM 88002

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This report describes a facility at the Atmospheric Sciences Laboratory (ASL) for the measurement of hot gaseous plume radiative transfer in the atmosphere. The measurement sequence, by using a Fourier transform spectrometer (FTS), required to extract the hot-through-cold radiance, the source radiance, the hot cell absorption, and the long path cell transmission is detailed. Problems peculiar to hot gaseous radiative transfer measurements

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20. ABSTRACT (cont)

are addressed as well as the impact on military systems. The direction of upcoming measurements to be performed with this unique ASL facility is also described.

PREFACE

The authors thank Robert L. Spellicy for many helpful discussions concerning the solutions to problems associated with "hot-through-cold" radiative transfer measurements. They extend their appreciation to Richard G. Dixon for design and fabrication of several system components including the hot cell gas filling system, the purge housing, and the system table supports. The authors also thank Young P. Yee for his review of this report.

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INTRODUCTION

Tactical and strategic vehicular and aircraft targets are observed in the infrared (IR) bands in general by both gray body radiation of the equipment frame and by hot gas radiation from the exhaust plume. It is imperative for Army systems designers to have validated models for predicting these radiance levels to build or improve their detection systems. Because of their mobility and versatility in terms of required landing terrain, helicopters play an ever expanding role in military activities. Yet, because they are slow moving or stationary, they are highly vulnerable to enemy antiaircraft weaponry. Hence, the detection and suppression of aircraft signatures, which may be made possible as a result of model validating "hot-through-cold" radiative transfer measurements, is a vital issue in a wide variety of military scenarios. The advantage of long-range detection is shown in the scenario pair of figure 1a and b. At present, some helicopter signatures (visible and IR) have been addressed by the helicopter IR detection estimate (HIDE) model.[1] Use of the HIDE model has resulted in several system design changes such as low spectrally reflecting paints, modification of helicopter window configurations, and introduction of jammer designs for antihelicopter missiles. Still, existing models and data bases do not accurately characterize the hot gas IR plume or the radiative transfer of the plume emissions through the atmosphere. Much of this uncertainty can be eliminated if the correlation between the hot gas emission and atmospheric-path absorption lines are accurately modeled. Figure 2 shows that either visibility or range reduces the visible contrast; the plume's hot gas IR emission dominates the signature. With today's fuels, the vibration-rotation bands of the IR active water vapor and carbon dioxide molecules (H_2O and CO_2) dominate the plume spectrum.[2]

A limited number of controlled "hot-through-cold" radiative transfer measurements have been made which demonstrate the existence of correlation effects between the hot emission and cold absorption line spectra of like species.[3] [4] Statistical band models have been developed which appear to

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[1]Steve Smith and Dick Higbey, 1974, "HIDE Computer Model an IRCM Evaluation Tool," Proceedings of the 12th Infrared Imaging Systems (IRIS) Symposium on IR Countermeasures, 2:7

[2]Westinghouse Electric Corporation, 1974, Evaluation of IR Countermeasures Infrared Suppressor Report, prepared for Program Manager, US Army Aviation Systems Command, AMCPM-AEWSPS, under Contract DAAJ01-72-0447, Exhibit A, Data A003

[3]G. H. Lindquist, C. B. Arnold, and R. L. Spellicy, 1975, "Atmospheric Absorption Applied to Plume Emission. Experimental and Analytical Investigations of Hot Gas Emission Attenuated by Cold Gases," AFRPL-TR-75-30, Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, CA. AD A015075

[4]Stephen J. Young, 1977, "Evaluation of Nonisothermal Band Models for H_2O," J Quant Spec Rad Trans 18:29

HELICOPTER NOT DETECTED AT LONGER RANGE

(a)

REMOTE OBSERVATION OF HELICOPTER

(b)

Figure 1. Scenario pair depicting the advantage of long-range detection of enemy helicopters and advantages of signature suppression.

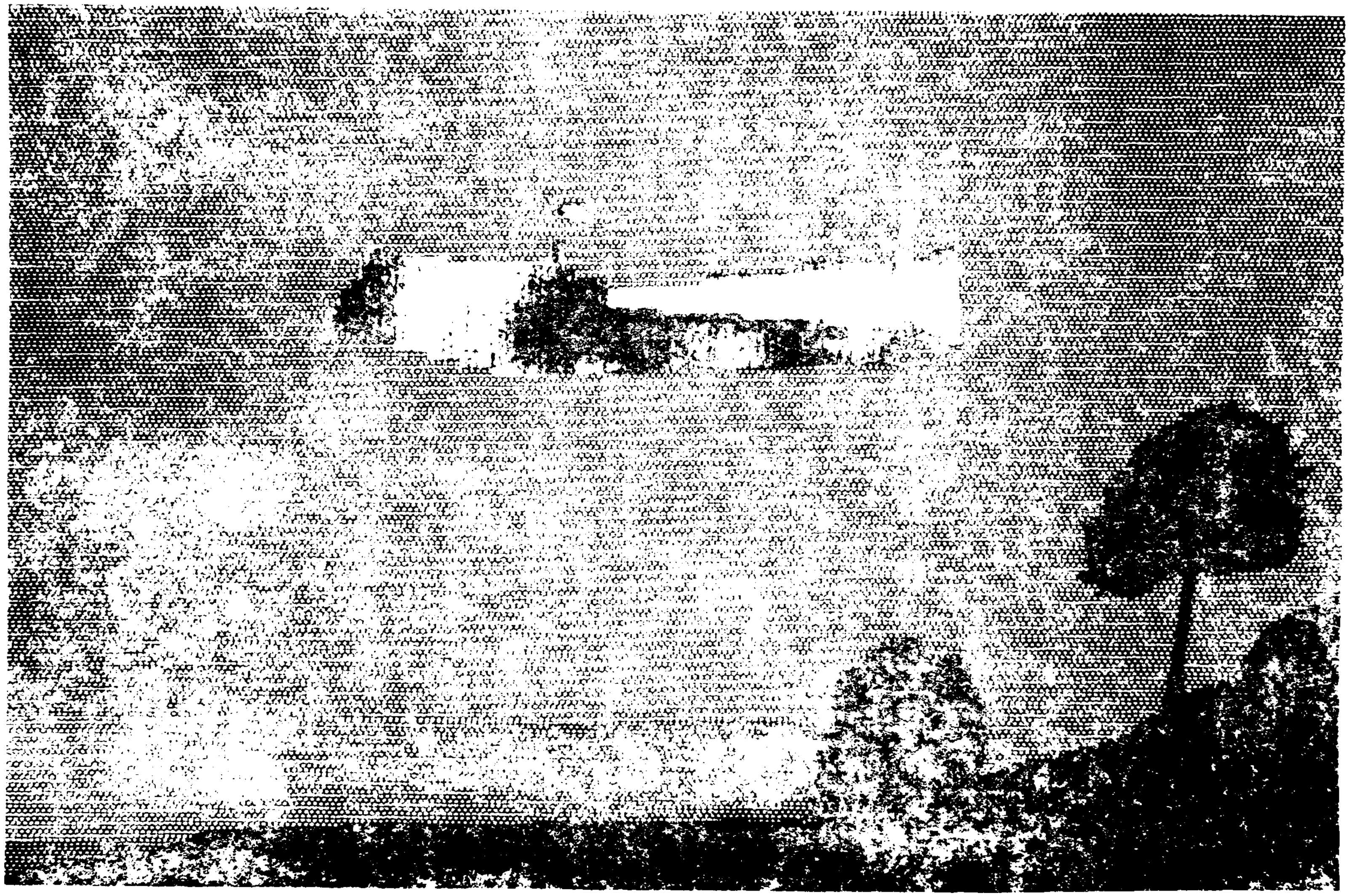

Figure 2. A HIDE model simulation of a helicopter gray body IR signature is shown against a background. The hot exhaust is the prominent feature.

adequately handle these correlation effects,[5] but an extensive set of parameters is required before the models can be adequately tested or used to significantly improve current predictive capabilities. The band model approach to the characterization of correlation effects has distinct advantages over other approaches (for example, high resolution definition of both the plume emission and atmospheric absorption) in that correlation effects are accounted for at moderate resolution by treating the total path (plume and atmosphere) as a single highly inhomogenous path. Hence, the moderate resolution of the system detectors does not have to be exceeded in calculating the plume transmission. This requirement is in line with the tracking requirements of rapid propagation predictions for which detector system models such as the HIDE model are tailored. Additionally, a validated band model could be used as an investigative tool which, in conjunction with well characterized propagated radiance measurements of an actual plume source, could be used to better define the physical makeup and hence quantitative definition of the IR plume source for existing vehicles and aircraft.

The measurements of "hot-through-cold" radiative transfer characteristics and the necessary band model parameters is relatively straightforward but not without experimental difficulties. The components required are basically a hot gas source, a controlled long atmospheric path, and a spectrally scanning detector. The unique hot gas cell source is temperature controlled from 500 to 1100 K and is fitted with appropriate cell windows capable of withstanding the high temperature and yet having the required broadband IR transmission characteristics. At present, the Army is interested in four detection bands between 1.5μm and 5.0μm.[6] Whether or not these are the optimum spectral bands has not been adequately addressed to date. A controlled long atmospheric path is obtained by using an ASL developed White-type absorption cell.[7] The cell is stainless steel, oil free, temperature controlled, bakeable, and automated for single person use with remote control mirror adjustments. Pathlengths up to 2 km can be obtained with the 21-m White cell optics.[8] The ASL facility is thus well suited to simulate atmospheric paths in the range between 0.6 to 3.0 km which are presently of primary interest. For simulations of higher altitudes, the optical depth of paths substantially greater than the actual 2 km geometric path can easily be matched. A Nicolett 7000 series FTS is available at the ASL facility. With spectral resolution to 0.04 cm^{-1}, the FTS can easily handle the typical 3 to 5 cm^{-1} moderate resolution needed for band model work and give the flexibility of later investigating high resolution

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[5]Stephen J. Young, 1977, "Nonisothermal Band Model Theory," J Quant Spec Rad Trans 18:1

[6]Westinghouse Electric Corporation, 1975, Notes on Evaluation of IR Countermeasures; Subject: Standardized Detector Responses, reported to US Army Aviation Systems Command, AMCPM-ASE, under Contract DAAJ01-72-C-0447, (P6C), Data Item F0B

[7]Wendell R. Watkins and Richard G. Dixon, 1979, "Automation of Long-Path Absorption Cell Measurements," Rev Sci Inst 50:86

[8]John U. White, 1942, "Long Optical Paths of Large Aperture," J Opt Soc Am 32:285

"hot-through-cold" propagated radiance for potential long-range plume detection using narrow-band sensors. These three major pieces of equipment (the hot gas source, the long path absorption cell, and the FTS) comprise the core of the unique ASL facility for investigating hot gaseous plume radiative transfer.

THEORY AND BACKGROUND

The basic problem of correlation of emission and absorption lines of like gaseous species stems from the approach most existing models take in assessing the "hot-through-cold" radiative transfer. The HIDE model, for example, characterizes the plume emission separately from the atmospheric path transmission. The source and transmission spectra are generated at moderate resolution ~5 cm^{-1} which is nearly two orders of magnitude larger than the typical half-widths of the gaseous CO_2 and H_2O lines in the 1.5μm to 5.0μm region.[9]

The moderate resolution hot gas radiance spectrum is then multiplied by the moderate resolution cold atmospheric transmission spectrum. However, this procedure generally does not give the correct moderate resolution "hot-through-cold" propagated radiance spectrum if correlation is present. Mathematically, this multiplication is equivalent to the fact that the product of the means is not generally equal to the mean of the products for two correlated sets of numbers.

The plan of attack that has been developed for addressing the correlation problem is to: (1) define the deficiencies in existing noncorrelating radiative transfer models, (2) validate existing correlating statistical band models (including refinement of the presently inadequate band model parameter data base), and (3) determine the models appropriate for improving the predictive capabilities of existing system models. This process requires accurately characterized measurements of "hot-through-cold" radiative transfer and hence the assembly of a facility with this capability. Before giving a detailed description of the measurements of the ASL facility, a brief outline of statistical band model theory is in order to better define the impact these measurements will have on improving calculational capabilities for propagated radiances.

Several facets are important to statistical band models. These facets are tailored to account for correlation effects for moderate spectral resolution "hot-through-cold" radiance calculations and require temperature dependent parameters with moderate spectral resolution instead of a complete high resolution listing of absorption and emission lines. They are presently limited by lack of intermediate temperature (500 to 1200 K) measurements from which to extract the band model parameters. Finally, the facets must be validated by using "hot-through-cold" radiative transfer data spanning the linear, square root, and transition regions of the curve of growth.

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[9] R. A. McClatchey et al, 1973, AFCRL Absorption Line Parameter Compilation," AFCRL-TR-73-0096, Air Force Geophysics Laboratory, Hanscom Air Force Base, MA

The secret to the success of statistical band models in accounting for correlation effects is that the theoretical approach does not separate the plume from the atmospheric path. Instead, in the band model the whole path (the plume and intervening atmosphere) is considered as a single highly inhomogenous path and the combined propagated radiance observed at a location removed from the plume source is calculated (figure 3). There is, of course, a strong spectral dependence of the emitted, absorbed, and propagated radiance on frequency and path characteristics. Two limiting cases must be handled appropriately by the band models as a function of optical depth. Line strength grows linearly with increasing optical depth when the line is isolated and relatively weak but grows quadratically after the line has become strong with an opaque central maximum as shown in figure 4. Band model methods are tailored to match these two limiting conditions and relatively recently have been modified to correct for problems unique to the intermediate regime (as [5] extensively detailed in a review article on band models by Young).

Several physical assumptions have been made to apply statistics to the emissions or absorptions of a band of spectral lines. Neither these assumptions nor their justifications will be discussed in detail. Basically, the emission and absorption lines in a given spectral region $\Delta\nu$ are assumed to be randomly distributed and the radiance at a remote point is theoretically calculated, from a hot gaseous plume, due to the assumed distribution of spectral lines in the region $\Delta\nu$. This procedure is performed in terms of a distribution function for the line strengths and results in a formulation dependent upon effective parameters for the path related to the isothermal band model parameters α and β (essentially the strength-to-spacing and the width-to-spacing ratios, respectively). The time saving element in the statistical band model approach is that the frequency integration can be done once and for all separately from the spatial integration along the path. This procedure precludes the necessity for a detailed compilation of individual line positions, widths, and strengths. For a particular calculation, the effective parameters are evaluated by integrating the isothermal parameters over the particular path of interest and substituting these into the appropriate band model expressions. The isothermal band model parameters are obtained by a series of measurements of the gas radiance and absorptance for a variety of hot gaseous H_2O and CO_2 mixtures and temperatures.

Evaluation of the atmospheric propagation of IR signatures for vehicles and aircraft generally requires modeling both frame and plume emissions. In general, the calculation of frame emissions and their propagation through the atmosphere can be treated with reasonable accuracy using existing multifaceted models and standard atmospheric transmission codes once the skin emissivities, reflectivities, and temperatures are known. The problem of evaluating plume emissions and their atmospheric propagation, however, is far more difficult, not only because of a high degree of spectral structure present as well as the complication of line position correlation between like emitting and absorbing gas species, but also because of the lack of a sufficient data base for either "line-by-line" or statistical band model calculations.

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[5] Stephen J. Young, 1977, "Nonisothermal Band Model Theory," J Quant Spec Rad Trans 18:1

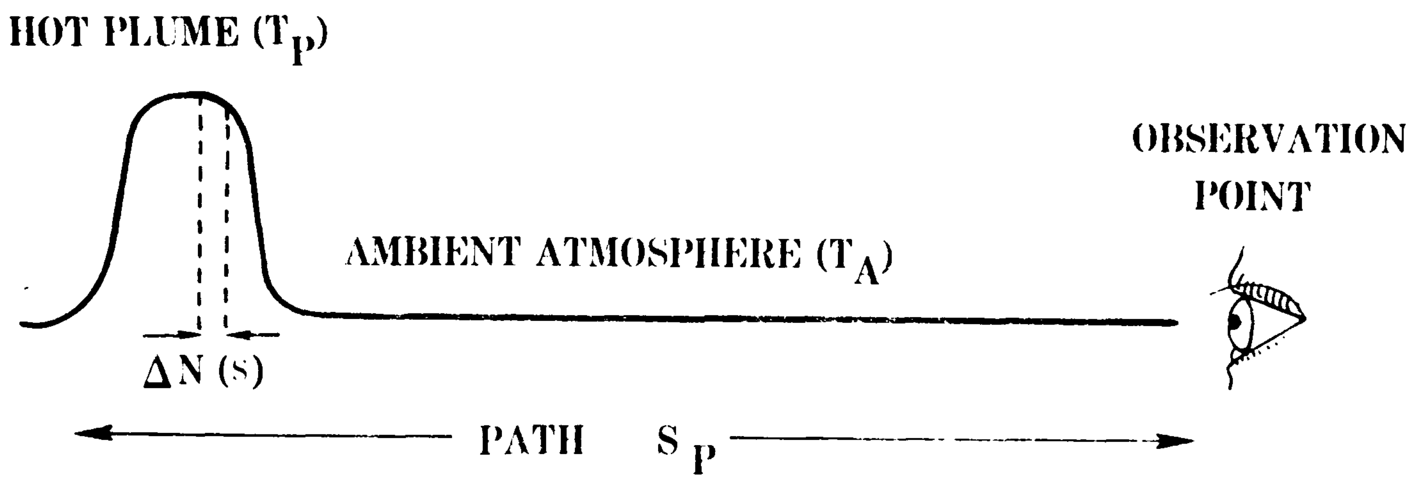

Figure 3. Depiction of the radiance contribution, ΔL, from a location, s, to the total observed radiance of the path, S_p, which contains the hot gas plume.

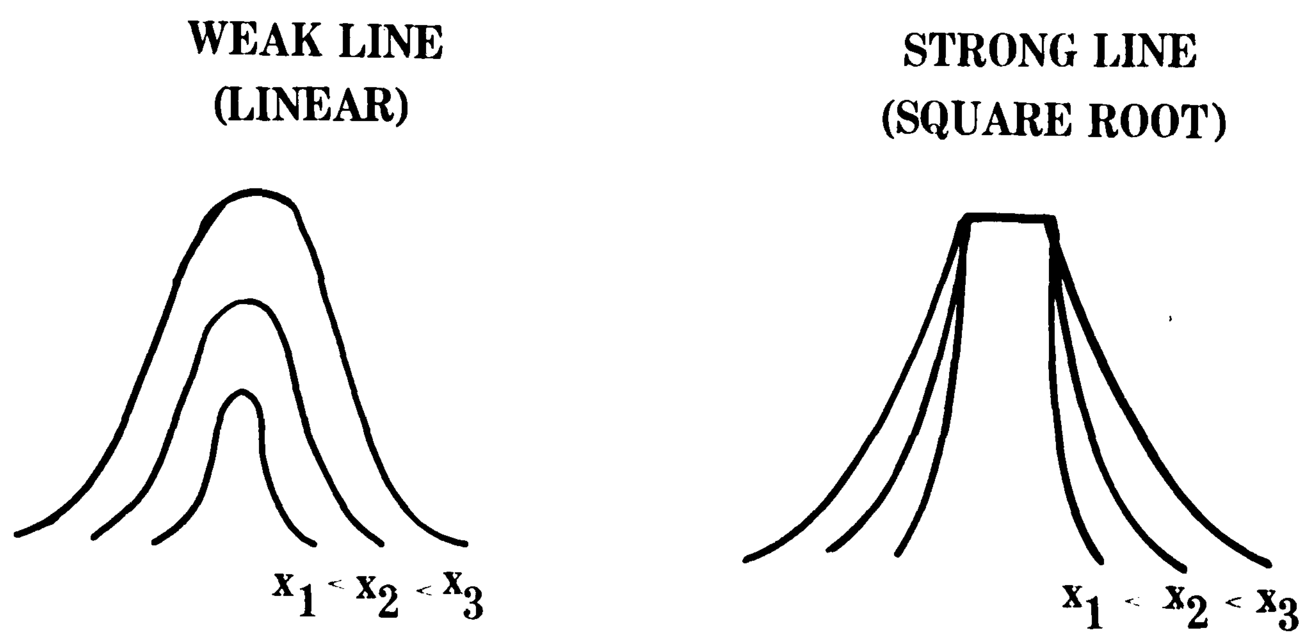

Figure 4. Line strength dependence on increasing optical depth, X, for weak and strong line limits.

The "line-by-line" approach, because it sums the contributions of the individual spectral lines and does so at a resolution small compared to a typical line width, inherently accounts for line correlation and spectral structure. Unfortunately, this type of calculation is usually prohibitively expensive and is limited to temperatures below 700 K, the temperature regime for which the line parameter atlas[9] contains all or most of the significant spectral lines. Also, evaluation of the required line parameters (line strength, line position, and line width) at elevated temperatures is an involved process which is in general not warranted (except in the wings of absorption bands) because the increased line density and inherent line overlap destroys the high resolution structure. Band models, however, are not so limited because the band model parameters can be generated in a somewhat straightforward manner regardless of the line density or line overlap.

The available band model parameters are the National Aeronautics and Space Administration (NASA) (General Dynamics) parameters[10] and those derivable from the Air Force Geophysics Laboratory (AFGL) atmospheric absorption line tabulation.[9] The NASA parameters for water vapor are measured values, based on emission and absorption measurements by using a long strip burner (θ > 1200 K), which were extrapolated to cover temperatures below 1200 K, while the CO_2 parameters were derived from theoretical calculations based on observed spectroscopic parameters for band positions but relied on harmonic oscillator approximations for the excited state band strengths. In general, the NASA H_2O parameters give reasonable agreement with observed radiance levels at temperatures near or above 1200 K, while the CO_2 parameters are seriously in error in the 2.7μm and in the 4.3μm bands at 1200 K. Also, as expected, the NASA parameters do not accurately predict atmospheric transmission or low temperature emissions because of their dependence on high temperature data.

Parameters derived from the AFGL compilation have exactly opposite characteristics because the tabulation, being suited for atmospheric applications, does not contain high rotational lines or excited state bands. Water vapor parameters generated from this tabulation show reasonable agreement with observed radiance levels near band centers, even at temperatures about 1200 K, but seriously underpredict the radiance in the band wings. For CO_2 a similar situation is seen in the 4.3μm band while the 2.7μm band is underpredicted throughout. At lower temperatures, such as those encountered in the atmosphere, the AFGL generated parameters give reasonable agreement with transmittances in both the 4.3μm region and the 2.7μm region.

Therefore, two separate sets of band model parameters may be used at either elevated temperatures (NASA, θ > 1200 K) or near atmospheric temperatures (AFGL, 300 K < θ < 700 K). However, no such set exists for intermediate

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[9] R. A. McClatchey et al, 1973, AFCRL Absorption Line Parameter Compilation," AFCRL-TR-73-0096, Air Force Geophysics Laboratory, Hanscom Air Force Base, MA

[10] C. B. Ludwid et al, 1973, Handbook of Infrared Radiation from Combustion Gases, NASA SP-3080, Marshal Space Flight Center, Huntsville, AL

temperatures (700 to 1200 K) of importance to aircraft or vehicular detection except for those generated by Young through interpolation of the NASA and AFGL values.[4] As expected, the lack of intermediate temperature (700 to 1200 K) band model parameters is accompanied by a lack of controlled intermediate temperature data required for either validation of the models or extraction of the required parameters.

EXPERIMENTAL FACILITY

As discussed in the introduction of this report, the basic "hot-through-cold" measurement system is comprised of three major pieces of equipment--the hot gas source, the long path absorption cell, and the FTS. Figure 5 shows the equipment in an experimental setup and also shows a blackbody source, f-number matching optics, and two directional mirrors which are used to steer the beam through the White cell for extracting "hot-through-cold" radiance spectra or to bypass the cell for extracting separate spectra of the hot gas source and cell transmission. By using this setup, absorption cell pathlengths of more than 1.0 km can easily be obtained. The hot cell, White cell, and FTS were optically coupled so that a rapid rate of data collection could be maintained for a 1.0 km pathlength without losing any FTS resolution. The initial system alignment was accomplished by replacing the blackbody source with a helium-neon (HeNe) laser. The f-number matching lenses, the optical axis of the hot cell, and the directional mirrors were carefully positioned one element at a time. A second and permanent HeNe alignment laser, to be discussed in the following paragraph, was coupled into the FTS so as to retrace the optical path back to the first HeNe laser. The first HeNe laser was removed and then the blackbody source was put back into the system. This arrangement allows precision visible alignment of the entire system independent of the source intensity.

The Nicolet 7000 series FTS tailored for this measurement system is shown in figure 6. The FTS accommodates a 5-cm diameter input and gives up to 0.06 cm^{-1} resolution between 10 to 5000 cm^{-1}. The resolution is variable from 0.06 to 8 cm^{-1}, which meets the moderate and the high resolution requirements for "hot-through-cold" measurements. The presently used germanium coated KBr beamsplitter (BSIR in figure 6) is designed for use in the 400 to 5000 cm^{-1} range. InAs, HgCdTe, and InSb detectors (D in figure 6) are on hand and span the entire 1.5μm to 10.0μm region. The FTS data system is quite flexible and allows for storing the interferogram data on discs as well as displaying and comparing the resulting transform spectra on an integral CRT. Finally, the centerline laser prism (P1 in figure 6) used for monitoring the FTS mirror movement was silvered on the back surface. This prism, in conjunction with a flat positioning mirror M6 and the second and permanent system HeNe alignment laser (described earlier), allows visible alignment of the entire optical system of figure 5 including the FTS input beam.

The 21-m long path absorption cell used in the "hot-through-cold" measurement system has already been used in several previous experiments including water

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[4]Stephen J. Young, 1977, "Evaluation of Nonisothermal Band Models for H_2O," _J Quant Spec Rad Trans_ 18:29

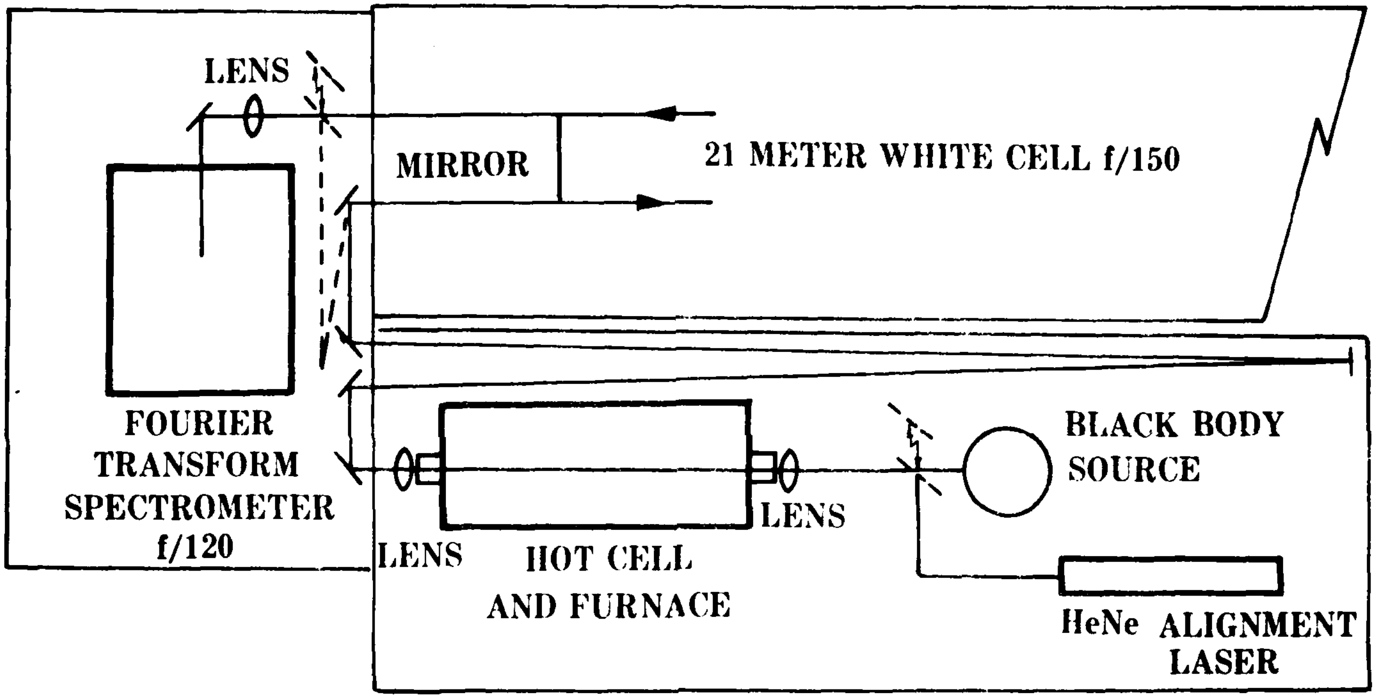

Figure 5. Schematic of the experimental setup for "hot-through-cold" radiative transfer measurements.

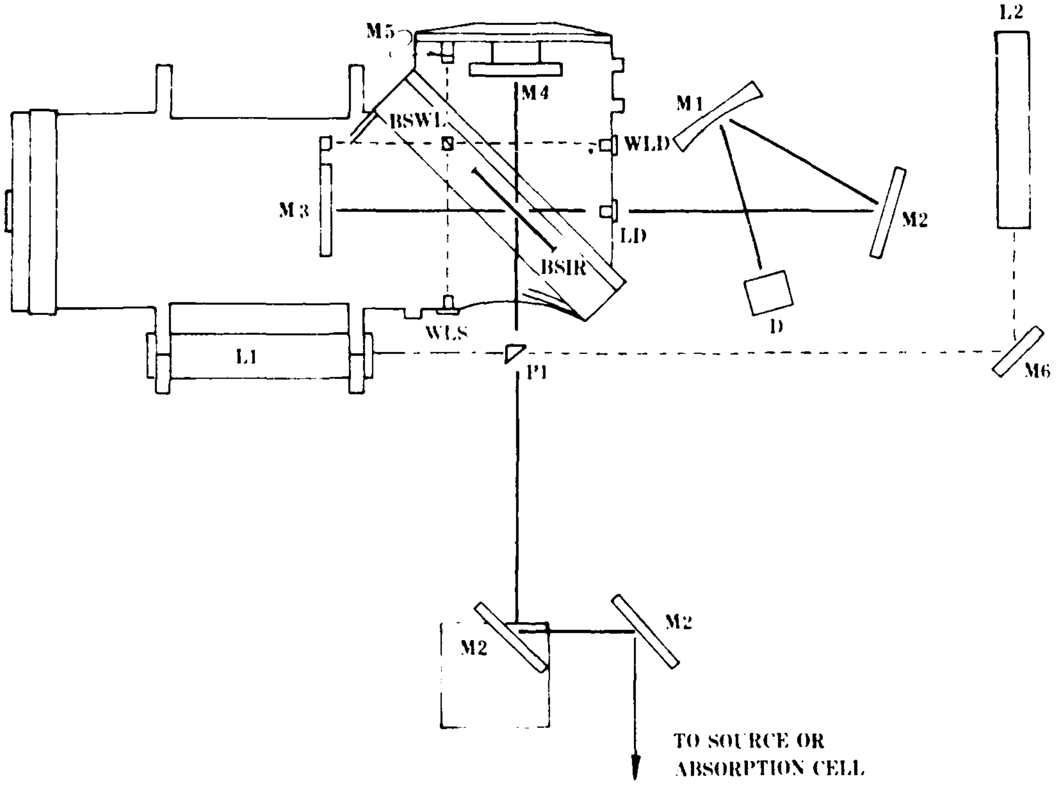

Figure 6. Detailed schematic of the Nicolet 7000 series FTS where M1 is an off-axis parabolic mirror with 20.8-cm focal length, D is the system detector, M2 are flat directional mirrors, M3 is the moving mirror assembly, M4 is a fixed mirror for the IR beam and reference laser, M5 is a fixed mirror for the white light source, BSWL is the white light beamsplitter, BSIR is the IR/reference laser beamsplitter, LD is the centerline reference laser detector, WLD is the white light detector, WLS is the white light source, L1 is the reference HeNe laser, P1 is the centerline laser prism with silvered back surface, M6 is a micrometer adjustable flat mirror, and L2 is the system HeNe alignment laser.

vapor absorption studies.[11] [12] [13] The automated mirror controls allow simple one person alignment as well as path differencing[14] capability when measuring the cell transmittance. The cell gas handling system, including an oil free turbo molecular pump as well as the cell temperature control system, allows relatively high water content atmospheres to be used. Since the ends of the cell which contain the mirrors can be heated independently from the rest of the cell,[15] relative humidities approaching 100 percent can be used if necessary. Also, since an FTS is used in conjunction with the cell, the purity of the cell's atmosphere can easily be determined.

The most challenging technical problem encountered in developing this system was the design and fabrication of a heatable absorption cell employing long-wavelength (transmits well through 6.5μm) transmitting yet brittle windows which could maintain a vacuum seal without breaking even when temperatures were recycled between ambient to at least 1100 K. The final design, which was found to be highly successful, is shown in figure 7. This design uses dual windows so that minimal pressure differential can be maintained across the hot inner window, with dual "O"-ring seals on both windows to allow for thermal expansion. The inner SrF_2 windows are sealed with silver coated metallic "O"-rings while the outer cooler windows (SrF_2 or BaF_2) are sealed with silicone "O"-rings. Preliminary tests have shown that this cell is capable of maintaining a vacuum seal at temperatures from ambient to at least 1000 K and that the cell can be repeatedly cycled over this range without damage to the inner windows. The cell is electrically heated, and the temperature is monitored internally with three thermocouples to insure uniformity.

An elaborate fill system shown in figure 8 for producing hot H_2O and CO_2 gas fills is attached to the hot gas cell. The entire fill system can be evacuated by using a cold-trapped vacuum pump. The pressure is monitored by using a 0- to 1000-torr pressure gauge. The water is boiled into the system from a constant temperature water bath. The gas can be circulated through the inner chamber, and the dew point monitored even when a mixture of gases is used. Because the water concentrations in simulated plumes are well above the room temperature dew point, all the gas fill system lines which contain H_2O are

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[11]Wendell R. Watkins and Kenneth O. White, 1977, "Water-Vapor-Continuum Absorption Measurements (3.5-4.0μm) Using HDO Depleted Water," Opt Lett 1:31

[12]Kenneth O. White et al, 1978, "Water Vapor Continuum Absorption in the 3.5-4.0μm Region," Appl Opt 17:2711

[13]Wendell R. Watkins et al, 1979, "Pressure Dependence of the Water Vapor Continuum Absorption in the 3.5-4.0μm Region," Appl Opt 18:1149

[14]Wendell R. Watkins, 1976, "Path Differencing: An Improvement to Multipass Absorption Cell Measurements," Appl Opt 15:16

[15]Darrell E. Burch, 1980, "Recent Measurements of the 4μm H_2O Continuum," presented at the 1980 Annual Review Conference on Atmospheric Transmission Models, Air Force Geophysics Laboratory, Hanscom Air Force Base, MA

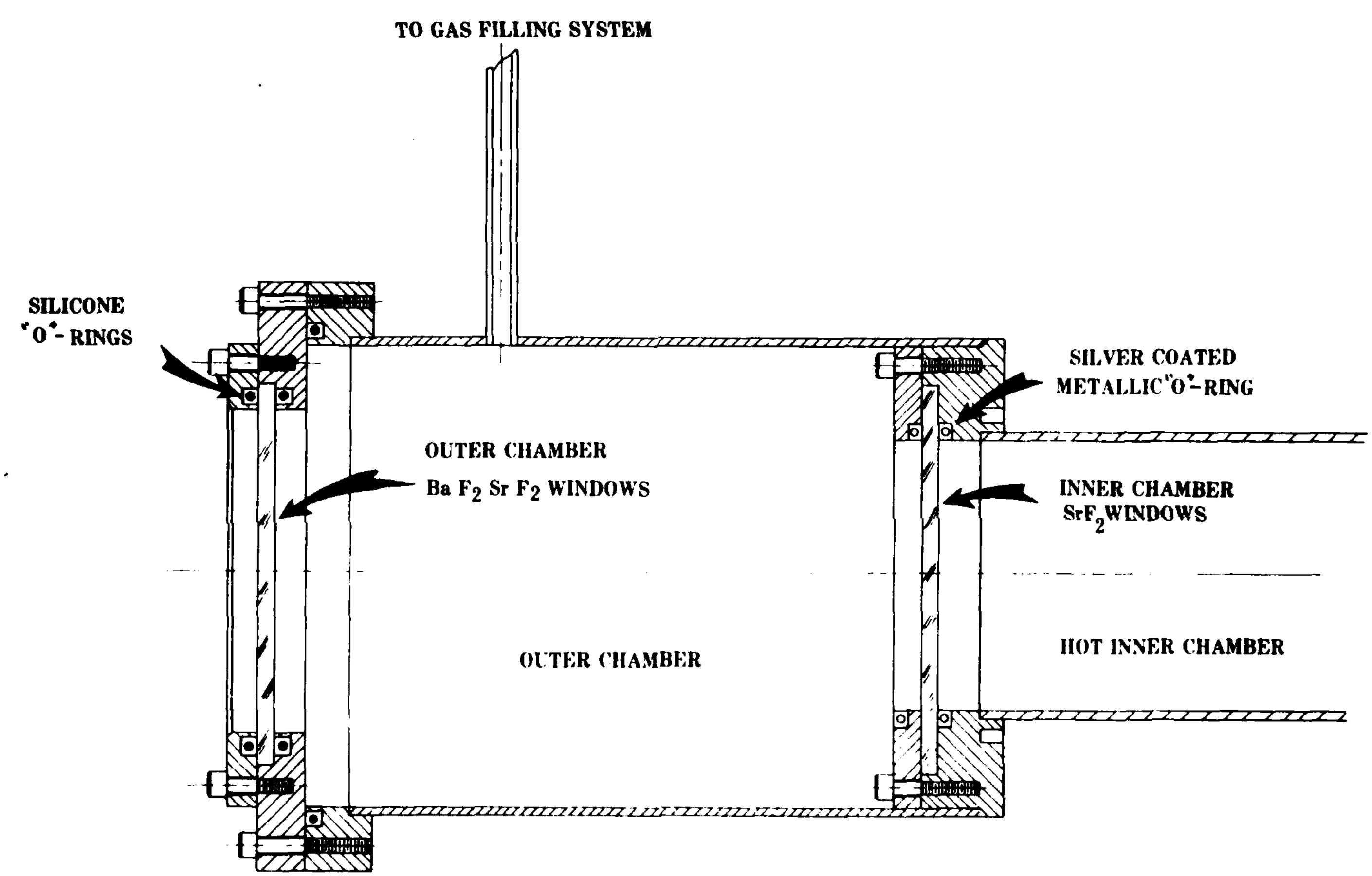

Figure 7. Diagram of vacuum sealing of the hot gas cell. The inner chamber is electrically heated and maintained at a constant temperature.

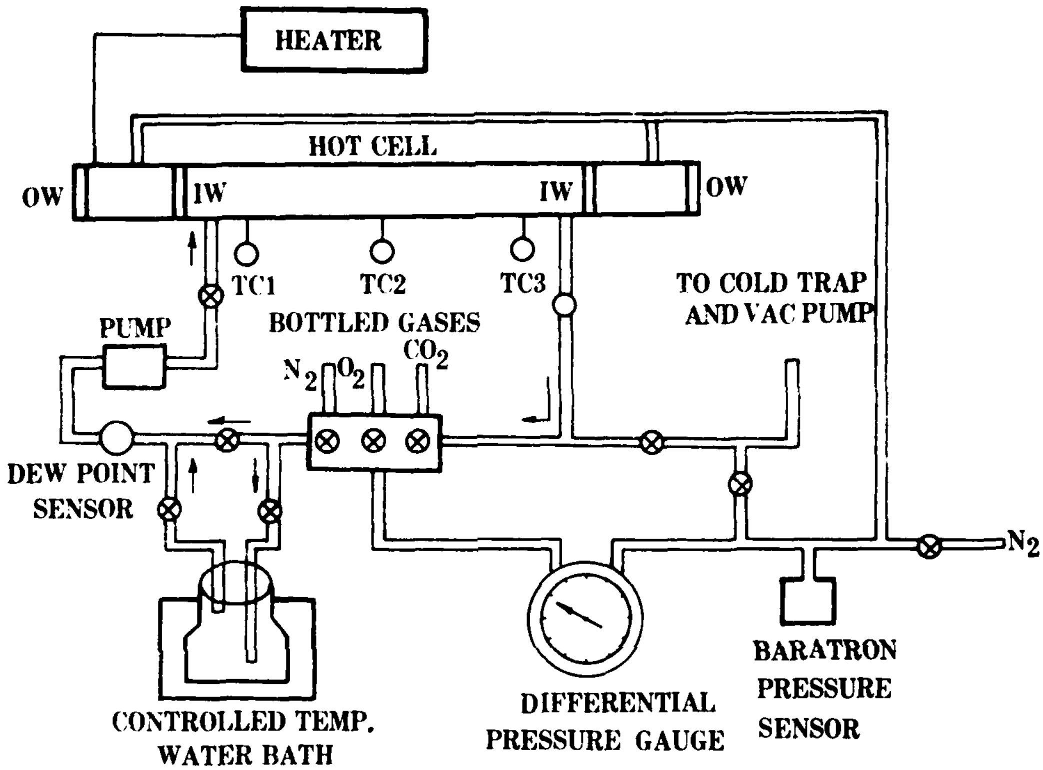

Figure 8. Schematic of the gas filling system for the hot gas cell where TC1, TC2, and TC3 are thermocouples for monitoring the gas temperature, and IW and OW are, respectively, the hot gas cell inner and outer chamber windows.

heated to 60°C to prevent condensation. CO_2, O_2, and N_2 can be introduced into the hot gas cell from high purity fill bottles. A separate fill bottle of N_2 is used for equalizing the outer and inner chambers of the hot cell, and the differential pressure across the inner windows is monitored with a two-sided 0- to 760-torr pressure gauge.

Because the input and output windows of the long path absorption cell are approximately 2 m above the laboratory floor, concrete pedestals were fabricated to elevate the surfaces of the 1.2-m by 3.6-m and the 1.2-m by 1.8-m optical tables used for mounting all of the system components. Since the room air contains absorbing gases, the entire system is housed in a purge box so that it can be filled with an inert gas to eliminate this background absorption.

MEASUREMENT APPROACH

The difficult task of developing a systematic measurement approach to obtain the "hot-through-cold" measurement spectra for system model validation and the necessary data base for statistical band model use was greatly simplified by the assistance of Robert L. Spellicy, an expert in this field. After reviewing his previous work,[3] present efforts in related areas,[16] and helpful discussions, we defined a complex yet efficient measurement procedure. In retrospect, the etalon and multiple reflection effects of the present hot cell design will be eliminated from any future hot cells by using wedges for windows and tilting the windows off axis.

The quantity which is sought is the hot gas radiance times the transmission of the absorption cell gas. Unfortunately, other radiance sources and transmission losses must be accounted for or ratioed out of the measured radiance quantity. The first step is to examine the radiance from the hot gas cell depicted in figure 9. Excluding the multiple reflection terms for the present, there are two sources of radiance from the hot gas cell: (1) the hot gas radiance, $L^*\alpha_g$, where L^* is the Planck function for the inner cell temperature, and α_g is the absorption of the hot cell gas; and (2) $L^*\alpha$ which is the radiance from the inner cell windows which are also hot. Here α is the absorptance of the windows. These two sources result in three radiance terms which exit the hot cell:

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[3]G. H. Lindquist, C. B. Arnold, and R. L. Spellicy, 1975, "Atmospheric Absorption Applied to Plume Emission. Experimental and Analytical Investigations of Hot Gas Emission Attenuated by Cold Gases," AFRPL-TR-75-30, Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, CA. AD A015075

[16]Robert L. Spellicy, Progress Reports 26 Jan 80 - 29 Feb 80 and 29 Feb 80 - 31 Mar 80, under grant Environmental Protection Agency Grant R-805956-01, by OptiMetrics, Inc., PO Drawer E, White Sands Missile Range, NM

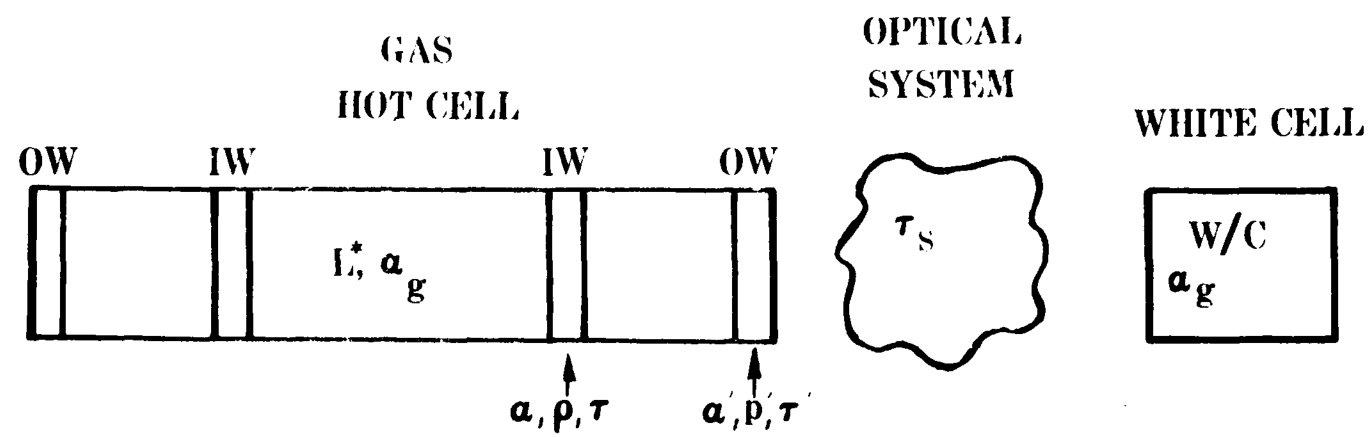

Figure 9. Depiction of the emitting, absorbing, reflecting, and transmitting elements of the "hot-through-cold" measurement system.

$L^{*}\alpha\tau'$ from the front inner window where τ' is the transmission of the outer front window of the cell,

$L^{*}\alpha_g\tau\tau'$ from the hot gas where τ is the transmission of the inner front window of the cell, and

$L^{*}\alpha(1 - \alpha_g)\tau\tau'$ from the back window where $(1 - \alpha_g)$ represents the transmission of the hot cell gas charge.

The amount of the radiance reaching the FTS is diminished by the transmission of all the optics in the system, τ_s, as well as the transmission of the long path White cell gas, $\tau_g^{w/c}$. Hence, the propagated radiance seen at the FTS, Y, is given by:

$$Y = [L^{*}\alpha\tau' + L^{*}\alpha_g\tau\tau' + L^{*}\alpha(1 - \alpha_g)\tau\tau']\tau_s\tau_g^{w/c} \; . \tag{1}$$

Grouping terms of hot gas radiance and cell window radiance yields

$$Y = L^{*}\alpha_g\tau_g^{w/c}\,[\tau\tau'\tau_s(1 - \alpha)] + L^{*}\alpha\tau_g^{w/c}[\tau'\tau_s(1 + \tau)] \; . \tag{2}$$

Note (as will be detailed later for multiple reflections) that for the window τ does not equal $(1 - \alpha)$ because of the window surface reflections. Also, for an empty hot cell $\alpha_g \rightarrow 0$ and the propagated radiance is given by just the second term on the right hand side of equation (2). This term will thus be referred to as a "cell" scan or

$$\text{"cell"} = L^{*}\alpha\tau_g^{w/c}\,[\tau'\tau_s(1 + \tau)] \; . \tag{3}$$

Then, to obtain the "hot-through-cold" propagated radiance, $L^{*}\alpha_g\tau_g^{w/c}$, evaluate $[\tau\tau'\tau_s(1 - \alpha)]$. To begin, α for the SrF_2 windows is on the order of 10^{-4} cm^{-1}, and hence $(1 - \alpha)$ goes to 1 within system measurement accuracies. To evaluate $\tau\tau'\tau_s$, a blackbody source is used. Its propagated radiance, Y_{BB}, through an empty hot cell $(\alpha_g \rightarrow 0)$ and absorption cell $(\alpha_g^{w/c} \rightarrow 0)$ is given by:

$$Y_{BB} = L_{BB}^{*}\,\tau'\tau\tau'\tau_s + L^{*}\alpha[\tau'\tau_s(1 + \tau)] \; , \tag{4}$$

where L^{*}_{BB} is the blackbody source radiance which can be calculated from the blackbody source temperature. Again the second term on the right side of equation (4) can easily be measured by blocking the blackbody source. This term will be denoted as the "cell MT" scan. Finally, τ and τ' can be calculated for the hot cell windows knowing the index of refraction n and n' since

$$\tau = (1 - \rho)^2 (1 - \alpha) \tag{5}$$

and

$$\rho = \left(\frac{1 - n}{1 + n}\right)^2 , \tag{6}$$

where ρ is the window surface reflectance. Therefore, by using equations 2 and 4, the "hot-through-cold" propagated radiance can be given by:

$$L^{*}\alpha_g \tau_g^{w/c} = \frac{Y - \text{"cell"}}{Y_{BB} - \text{"cell MT"}} L^{*}_{BB}\tau\tau' . \tag{7}$$

To begin the discussion of how mutliple reflections complicate the above analysis, the case of one inner window flat will be addressed. Figure 10 shows the resultant multiple reflections of an incident beam with intensity I_o where the beam experiences a reflection ρ and a transmission loss of $(1 - \alpha)$. Hence, for a wedge the transmitted beam intensity is simply

$$I_o(1 - \rho)^2(1 - \alpha) .$$

For the multiply reflected beam the resultant intensity, I, is given by:

$$I = I_o(1 - \rho)^2(1 - \alpha)[1 + \rho^2(1 - \alpha)^2 + \rho^4(1 - \alpha)^4 + \dots] , \tag{8}$$

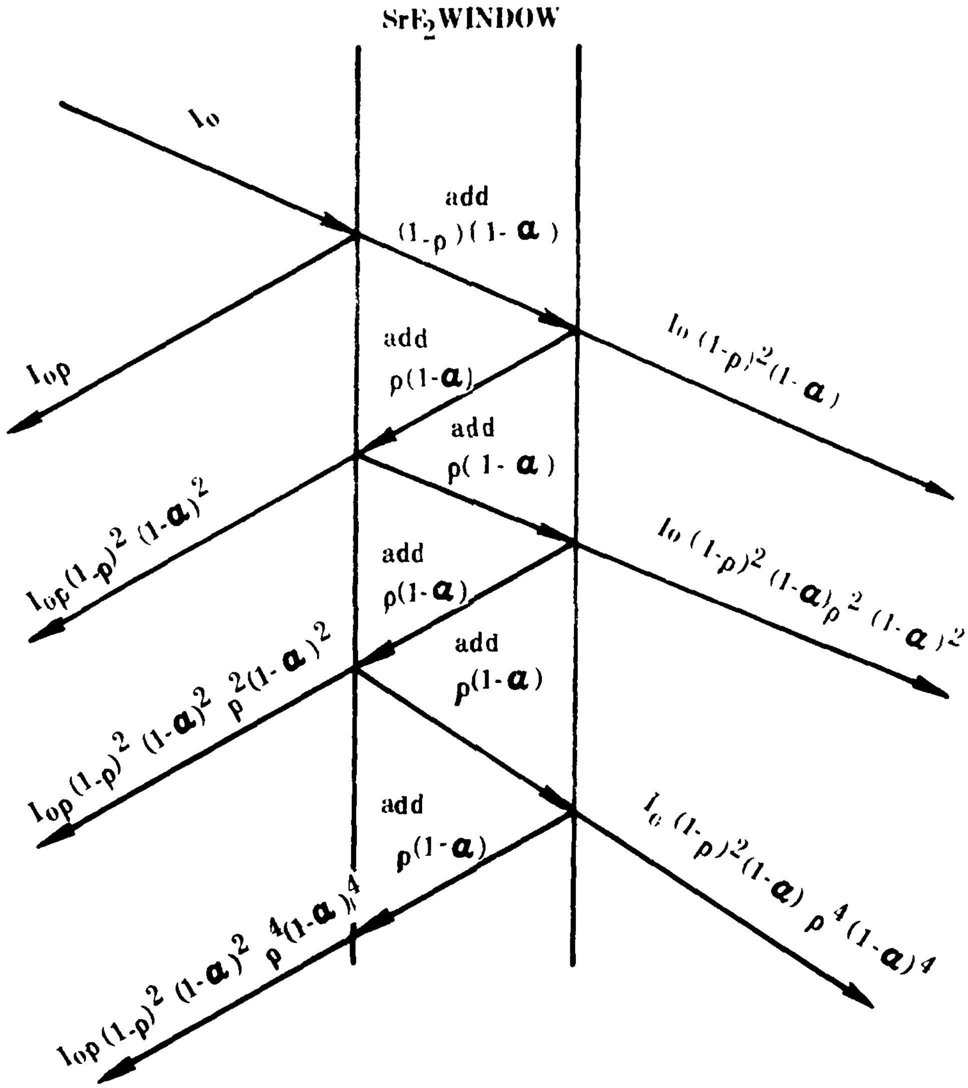

Figure 10. Schematic illustrating multiple reflections and transmissions of an incident beam of intensity I_0 where the SrF_2 window has surface reflectivity ρ and single pass absorptance α.

and, since ρ and α are between 0 and 1, the series identity

$$\sum_{i=0}^{\infty} x^i = \frac{1}{1 - x} \tag{9}$$

can be applied. This results in

$$I = I_0 \frac{(1 - \rho)^2(1 - \alpha)}{1 - \rho^2(1 - \alpha)^2} = I_0 T \tag{10}$$

where T is the window multiple reflection transmittance. A similar derivation can be used to get the multiple reflection window reflectance R. The resultant expressions are given by:

$$T = (1 - \rho)^2(1 - \alpha)/[1 - \rho^2(1 - \alpha)^2] \tag{11}$$

and

$$R = \rho\{1 + (1 - \rho)^2(1 - \alpha)^2/[1 - \rho^2(1 - \alpha)^2]\} \tag{12}$$

with similar expressions for T' and R' for the outer cell windows. When the multiple reflection terms are included, the resultant expression for the propagated "hot-through-cold" radiance becomes:

$$L^*\alpha_g\tau_g^{w/c} = \frac{Y - L^*\alpha\tau_g^{w/c}\,\tau_s[T'/(1 - R'R)]\{1 + T/[1 - R(1 - \alpha_g)]\}}{T'T\tau_s(1 - \alpha)/[1 - R(1 - \alpha_g)](1 - R'R)} \,. \tag{13}$$

A dependence of the second numerator term of equation 13 now appears upon α_g through the expression $\{1 + T/[1 - R(1 - \alpha_g)]\}$. This was not the case previously in equation 2 where multiple reflection effects were ignored. Fortunately, the "cell" scan for the multiple reflection case given by

$$"cell" = L^{*} \alpha \tau_g^{w/c} \tau_s [T'/(1 - R'R)][1 + T/(1 - R)] \quad (14)$$

is very similar to the second numerator term in equation 13. The only difference is the omission of the $(1 - \alpha_g)$ in the last term. For the cell windows used $T \cong T' \cong 0.94$ and $R \cong R' \cong 0.058$, and the resulting error in using the "cell" scan to approximate the second numerator term in equation 13 would be as follows for various values of α_g:

$$\frac{[1 + T/(1 - R)]}{\{1 + T/[1 - R(1 - \alpha_g)]\}} = \begin{matrix} 1.03 \text{ if } \alpha_g = 1.0 \\ 1.01 \text{ if } \alpha_g = 0.5 \\ 1.00 \text{ if } \alpha_g = 0.0 \end{matrix} \quad (15)$$

Whether this error is significant depends on the measurement error bound, and if significant it can be corrected to first order by using calculated correction coefficients.

The blackbody source can again be used for evaluating the denominator of equation 13 with the resulting approximation being given by

$$\frac{Y_{BB} - \text{"cell MT"}}{L_{BB}^{*} \tau_g^{w/c}} = \frac{T^2 T'^2 \tau_s}{(1 - R^2)(1 - RR')^2} . \quad (16)$$

The major difference other than simply terms of T, T', R, and R' is the omission of the $(1 - \alpha)/[1 - R(1 - \alpha_g)]$ term which again can be corrected for if necessary.

A typical set of measurements for determination of "hot-through-cold" radiance will then consist of:[16]

1. A "cell" measurement with both the hot cell and White cell empty
2. An absorption measurement of the hot cell gas
3. A radiance measurement of the hot gas through an empty White cell

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[16]Robert L. Spellicy, Progress Reports 26 Jan 80 - 29 Feb 80 and 29 Feb 80 - 31 Mar 80, under grant Environmental Protection Agency Grant R-805956-01, by OptiMetrics, Inc., PO Drawer E, White Sands Missile Range, NM

4. A transmission measurement of the White cell gas after filling by using either a direct measurement or path differencing

5. A "hot-through-cold" measurement for a given hot cell and White cell fill.

Measurements 1 through 4 are required to evaluate the denominator of equation 13; measurement 4, in conjunction with measurement 1, is required to evaluate the second term in the numerator of equation 13; and measurement 5 is required to determine the desired "hot-through-cold" radiance. This particular sequence of measurements also supplies the hot gas radiance and cold cell transmittance independently so that the product of these two may be compared with the measured "hot-through-cold" radiance to evaluate the significance of line correlation effects.

CONCLUSIONS

A measurement facility with unique capabilities for handling "hot-through-cold" radiative transfer measurements has been assembled at ASL. The system has been tailored for addressing problems of current Army interest of plume propagation model validation for intermediate temperature plumes (500 to 1200 K) over the 1.5μm to 5.0μm spectral range (provided the appropriate beam-splitters and detectors are used). The system has been designed to be as flexible as possible. Moderate 3 to 5 cm^{-1} resolution will be used initially, but the available FTS capability of up to 0.06 cm^{-1} has not been compromised through the design process. Likewise, the five-step measurement scheme which was selected allows for model validation measurements and assessment of correlation effects of like emitting and absorbing molecules on radiative transfer, and also provides the spectra required to assess the validity of the intermediate temperature data base now used in statistical band model calculations. Also, the capability of expanding the spectral range for measurements beyond the 5μm limit was not eliminated in the hot cell design by judicious choice of window materials.

The ASL facility can now be used to address a myriad of heretofore unaddressable experimental problems related to hot gaseous plume radiative transfer. Although the initial emphasis was to be placed on the 2.7μm H_2O band, the present FTS beamsplitter and detector configuration does not span the wavelength range between 1.5μm to 2.0μm. Hence, the longer wavelength end of the 1.5μm to 5.0μm range of the present detector systems will be addressed first with the resulting "hot-through-cold" measurements to be compared with existing model predictions to assess their degree of validity and define the scope and direction of subsequent measurements. If the band model parameter data base is found to be inadequate, an assessment for requirements for obtaining a usable data base will be made. Also, by postponing the 2.7μm investigation until a beamsplitter which also spans the 1.5μm to 2.0μm region is purchased, the subsequent necessity of duplicating the measurement spectra will be avoided. Once spectra are taken over a region, the scope of the analysis is essentially limited by funding levels only and not experimental measurement data collection.

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